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Sustainable Development in Chemistry, Engineering and Industry, spontaneous transition or innovation paradox?

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1. INTRODUCTION

In the field of chemistry and chemical engineering, research and development is resulting in quite new approaches such as the application of biotechnology in chemical processes and the introduction of micro-reaction systems using the new developments in micro(electronic) systems. Other areas of rapid development are product design, using the possibilities of advanced simulation and synthesis technologies, separation technology for instance through the use of membranes, and catalysis aiming for more rapid and efficient synthesis routes. Economists, politicians, the common citizens and business people alike expect much of these new opportunities delivered by science and engineering. Not only to ascertain continuing their own prosperity and to bring this also to so-called third world. These new developments in science and engineering are also expected to take away the undesired side effects that present chemical production processes and technology evoke. Even more, they are seen as vital to sustainable development, which is the reason why many governmentally funded R&D-programs exist to further develop technological options and why many more will be initiated in the coming years.

However, a question that comes into the mind is whether the amount of research and development will really change the actual processes and technologies used at present in the chemical industry. New approaches can and will be developed, but does that automatically imply that they indeed will be implemented in commercial applications? Will the use of biotechnology and the introduction of microsystems indeed evoke a trend shift towards a sustainable development in Chemistry, Engineering and Industry?
A simple ‘yes’ or ‘no’ to these questions is not possible. However, awareness is growing that successful innovation requires more than the development of new knowledge and new technological options. There is mention of a so-called ‘innovation paradox’, for instance in the policy debate on innovation in The Netherlands, referring to the lack of implementation of new, and promising technological options. More and more it is realised that innovation is a complex process, influenced by the interaction between science, policy and industry and closely connected to societal trends. We believe that up to now, there has been insufficient attention for the drivers and barriers that influence innovation processes. This paper states that sustainable development in Chemistry, Engineering and Industries requires that policymakers, industry and other stakeholders act upon a clear view on the economic, institutional and societal drivers and barriers that determine the speed and extent to which new technological options are implemented in practice. The approach discussed here is linked with the emergence of new instruments for more effective innovation policies (Smits 2004).

Starting sustainable development in chemistry

As in many other countries the Dutch government gives high priority to sustainable development. That requires transitions - fundamental changes in socio-economic structures that take care of functions in society such as energy supply, food and housing. Specific areas in which sustainable transitions are to be stimulated, have been defined. Chemistry is one of them because it is recognized as an essential function in the economy. Evaluating the options, possible policies and the conditions that are to be generated for transitions to take place, the ‘innovation paradox’ is it apparently exists has of course to

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be taken into account too. Therefore at the start of the process to draft policies for transitions for sustainable chemistry it was decided to make a first study to inventory and assess the essential factors involved. That would produce an 'Inception Paper'. The study had to involve all actors and stakeholders. It would form a first basis for future development of policies and programs and for further discussions with all stakeholders (Weterings etal 2004).

It was to provide an as complete as possible 'map' of:

- the visions in the field on possible sustainable transitions and opinions on their feasibility;
- the drivers that can start and stimulate innovation needed for transitions;
- the reasons innovation for sustainable transitions halted: the barriers and apparent dilemmas. Where these become visible, possible first solutions to overcome the apparent inertness should be suggested.

The method of the study

The study was performed by TNO and the WUR[1] on behalf of the Dutch Ministry of the Environment. The study was done in two steps.

The first involved interviews with 10 'opinion leaders' known to have clear and outspoken views on the direction chemistry development, technology and the chemical industry should take. Those included representatives from small businesses which operated in a (still) niche marked but with much innovation and showing 'disrupting' characteristics, from multinational companies which have stated that sustainable development is at the core of their activities, from research groups and from environmental groups which are already involved in 'critical discussions' with industry on these issues. That information was supplemented with views, policies and data from earlier studies and policy papers, from government, from industries and professional organisations of chemists and chemical engineers (Bruggink etal 2003, De Rooij etal 1999, KNCV 2003, Roerdinkholder etal 2001, STD 1997, Venselaar 2003, Weterings etal 1997).

The resulting first draft of the paper offered a very wide set of views, often contradictory of course. A lot of suggestions were given for steps to be taken to make transitions in specific areas possible. A substantial part of the interview time was used to discuss possible barriers, dilemmas and potential drivers for specific innovations. In fact all persons interviewed agreed on the fact that much potential was already available in the knowledge, new technologies etc. that has been developed during the last decennia.

Five well defined areas for sustainable development within chemistry became clearly staked out during the interviews and the further evaluation of earlier reports. Views, trends, barriers, dilemmas could be grouped quite logically in this way. These are and will be the basis for further discussions.

The intermediate report formed the input for the second step; a workshop in which a further 35 other 'opinion leaders' took part. They represented the whole chemistry community, industry, research institutes, academia, professional organisation, government and action groups and platforms on environmental and other issues relevant for sustainability. They were asked to comment, amend and criticize the draft inception report and the first tentative conclusions drawn. That added much more information and in particular views on the innovation barriers and dilemmas that may result in the unsuccessful implementation of promising technologies. It did actually not change the basic approach that had crystallized out from the interviews nor the selection of the five areas chosen.

In the end report all the suggested views on the factors involved for innovation: the barriers and dilemmas, trends and drivers are brought together in so-called 'issue-arenas' for each area of sustainable chemistry transitions. The final report will with the continuing discussion in fact always be 'a draft only'. And it is, certainly in this stage, an inventory only. Many of the given opinions and many ideas are actually contradictory. There is also no clear agreement on the course that specific developments should follow. But it brings into view in much more detail and clarity then before which are the real issues to be taken up for sustainable development. It makes, again, clear that more technology development alone in many cases is not the key to sustainable transitions in chemistry.

[1] TNO: Dutch Institute for Applied Research; WUR: Wageningen University and Research Institute

2. SUSTAINABLE DEVELOPMENT, DRIVER FOR INNOVATION

Sustainable development will not occur without innovation. On the other hand one should be aware that innovation as such will not automatically lead to sustainable development.

<u>A new millennium, a new challenge</u>

In the new millennium we will witness leading companies going beyond greening of their business. Their challenge for innovation is not only to compete in terms of profit, but also in their performance regarding societal concerns such as equity and third world labour conditions and their efforts to strengthen and safeguard the quality of the environment and preserve the resources for future global wealth. Nowadays one-sixth of the world's population accounts for more than 75% of the world's energy and resource consumption. Taking into consideration the world's population growth to 10 billion people in 2040, it is expected that there will remain less then 50 year of cheap energy resources. Further the rapid industrialisation in emerging countries can easily offset the environmental gains made in developed countries over the past decades: there is an expected over-exploitation of resources, an overuse of water for irrigation, lack of sewage treatment, more contaminated water and an increase of industrial emissions. Poverty in rural populations will further increase: this will lead to deforestation, overgrazing and loss of fertile soils, destruction of natural habitats, lack of sanitation and, generally, depletion of the world's renewable resources. Based on similar considerations regarding population growth and economic development the World Commission on Environment and Development in 'Our common future' (WCED 1987) already concluded that drastic steps towards a sustainable economic development are needed. Many studies show that it is also necessary on macro as well as micro economical grounds (Hart etal 1997, Prahalad 2002).

<u>A shift of focus</u>

In the last three decades, the chemical industry has already gone through a gradual shift from a reactive towards a pro-active attitude regarding environmental issues. Companies reduced waste problems and toxic emissions in response to a growing level of public pressure. The focus was on end-of-the-pipeline solutions and reduction of waste. Better insight and costs lead to the introduction of new technology to reduce and prevent wastes and emissions at the source. With sustainable development again a change will occur, attention will shift to the way companies manage their responsibilities, do business and respond to the wishes of society. New technology will accompany that (Venselaar 2004).

Compliance to legislation has become an integral part of general management responsibilities and leading companies introduced health and safety reporting as a part of the annual report and audit schemes. One of the more successful programmes in industry is the Responsible Care Program, introduced by the chemical industry in 1980s. So environmental care is gradually changing into 'care for sustainability', and is increasingly linked to business strategy, recognising opportunities and innovation. This challenge has taken up by many leading businesses, such as those which form the World Business Council for Sustainable Development.

<u>International and national policy development</u>

In Europe policy development aimed at sustainable development is emerging. Till some years ago most attention was on separate environmental issues but this is shifting gradually. Several strategy papers (so-called white papers) have been published during the last years by the EU on different subjects concerning products and production and the various 'sustainability issues' involved. These give also attention to the broader concept of sustainable development and to a more integral approach as is also outlined in the 2004 review of the EC environmental policy (EC, 2004a). An essential connection is made in the EC policy review with resource management and the ambitious EC Lisbon strategy. The latter has set an ambitious goal of achieving an economic growth of 3% annum, a doubling of GDP in 25 years. The review underlines that the social, environmental and economic costs of such growth must be avoided. Decoupling resource use and environmental depletion is a central theme of the EU Sustainable Development Strategy which is being developed. The European programs aimed at stimulating innovation through knowledge and technology development give sustainable development a prominent role, not only as a specific area for development but also as aspect that should be included in all development (EC2004b)

Chemical industry and hence chemistry and chemical engineering, have much to do with the European policies and the directives that emerge from those. Particular challenges pose for instance the already existing IPPC directive and the proposed REACH directive. Responding to these challenges in a sensible and ultimately the only effective way, also economically, is only possible through radical innovation.

Also on European level the discrepancy between the availability of scientific and engineering knowledge and the actual use of that in innovations in industry has been a source of concern for some time. The so-called ‘European paradox’ is an issue already for some time (EC 1995). It is also part of the discussion in the policy development for sustainable development (Schomberg 2002)

System innovation and transitions
As is described sustainable development has sprung from environmental care in phases. That can still be seen in the steps that are taken tot attain sustainability. It is shown graphically in figure 1 for the pathways to increased eco-efficiency (STD 1997, Weaver et al 2000).

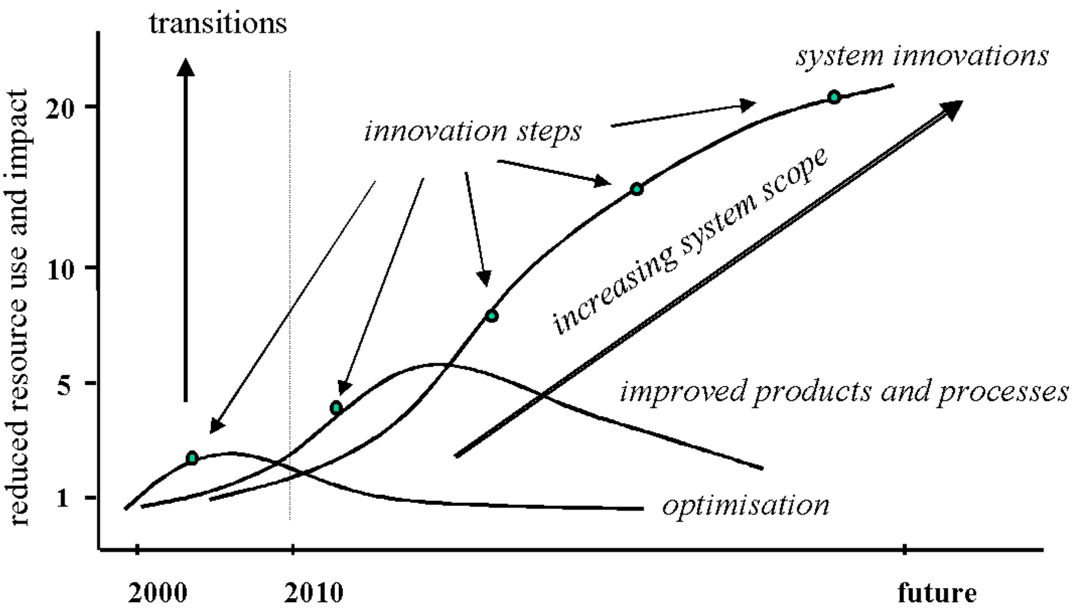

Figure 1 Phases in the development towards sustainability

Initially the environmental impact of activities is reduced by optimisation of existing activities, better waste management. Increasingly cleaner processes and cleaner products are being introduced. Nevertheless, the positive effect of that will be off-set by the ongoing growth. ‘Classic environmental management’ and pollution prevention through process and product improvement will not suffice in the long run. We need to do better and substantially so. Radically innovative and integrated approaches are needed. So-called ‘transitions’ are asked for, meaning coherent - and mutually strengthening - changes in technology, economy, culture and organisation. Such broad changes in socio-economic systems are needed to combine the necessary economic growth (more people requiring more prosperity and well-being) wealth and with preserving quality of life and the fundaments a sound economy can be based on.

Such radically innovative approach requires a better understanding of the way society is organised and the way it provides in the needs myriad needs that have evolved in the modern society we have. Technology is only a part of the development occurring within so-called socio-economic structures: the 'systems' that take care of the needs we have: food, travel, housing, leisure etc. They are made up of many components, technical and organisational ones. How such systems are organised and used is strongly influenced by 'culture', with differences between individuals, nations and larger regions. Such systems are continuously changing. When looking at it from a distance and in particular when looking back in time, major changes can be defined which are now coined 'transitions'. Examples are the introduction of steam power, the change from coal to gas for heating of homes, the introduction of cars for mass transport, the introduction of ICT. Technology changed fundamentally along with organisation and culture: society looked totally different afterwards. As example look at the cultural changes the new modes of telecommunication brought about and the 'shaping of Western society' by electricity and auto mobility.

Seen as a whole, such developments are far beyond management Changes occur under influence of global trends at the macro-level and ad hoc and short-term incentives at the micro-level. Some elements of change – especially at the micro level - can of course be managed, but that does not imply that the general outcome is within the realm of influence of any of the stakeholders.
Sustainable development however is to be, in essential aspects, a 'managed development' of such systems. Not towards a precisely defined image – a so-called blue print - of the future of course. However, it is possible to define a set of desired conditions that should be met in the future, and to draw roadmaps for future developments that enable society to meet these desired conditions at a certain point of time. Such managed development is quite a novel approach, never tried before, and clearly a controversial issue. Nevertheless it is seen as the essential approach for future development for a more stable future world society and economy.

It would be a misunderstanding to assume that such 'management' is the domain of government only. On the contrary, it is as much in the interest of businesses that an economy and society develops that can be sustained in the future, as it is for society itself.
Those businesses that can anticipate on future developments and requirements will thrive. Other will go broke in due course and be replaced by businesses that fit such new conditions. And by anticipating on the right way, they will bring sustainable development about. They thus manage it to a certain extent, although they will not be able to do that alone of course. The role of governments is to stimulate development, to set the framework and articulate the general direction such development takes as a result of political (and optimally democratic) processes in which all people and groups participate.

3. DEFINING THE AREAS FOR SUSTAINABLE CHEMISTRY TRANSITIONS

Chemistry as generic function

Chemistry[2] is an essential activity in our present society, although not always recognised as such. When discussing sustainable development in relation to chemistry (chemical engineering, chemical industry etc.) that role must be clear too. In accordance with the often used division in categories of economic goods and services proposed by Michael Porter we can make a division in end-use functions (such as food and housing), intermediate functions (such as transport and travel, communication) and generic functions (Porter 1990). Chemistry has a clear generic function. It supplies the basic resources, substances, materials and products that are needed for all other functions in society. Just as the other

[2] When using the concept chemistry people can mean different things. It can be the science, the actual activity of changing, separating or mixing substances or the whole of research, engineering and industry which does those things. In this context it is meant to be in this last.

generic function, energy supply, chemistry forms the basis of our present economy and society and economy. Developments in chemistry have an influence on all activities and in all layers of our society. Conversely a society that needs transitions requires new resources, materials and products and hence: novel chemistry.

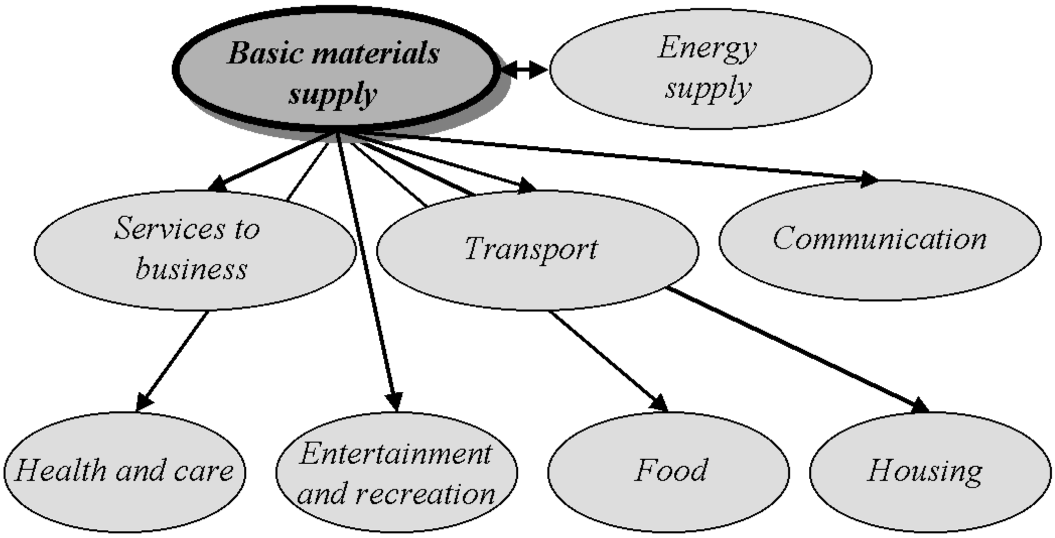

figure 2 Chemistry as generic function in society

The need for sustainable development has already proven a major driving force for new developments in chemistry and chemical technology. In reaction engineering, bioconversion, microsystems technology, catalysis etc. many promising developments are taking place. Substantial improvement in resource use efficiency is possible. Production installations can be downscaled and production time reduced. Furthermore compounds are being developed that are essential for sustainable development in many areas such as for energy, electronics and healthcare (Venselaar 2003).

<u>The role of chemistry in transitions</u>
What exactly would be the role of chemistry in transitions towards sustainable development? Generally speaking the answer is: chemistry is a major contributor to the sustainability of all intermediate and end-use functions in society by supplying the necessary 'sustainable' resources and making processes and products possible that are 'sustainable' in itself and can be used in a sustainable manner.

Transition towards sustainable chemistry takes place on three different levels: within the production sector itself, at the production chain level or at the level of society as a whole.
On sector level the chemical industry should make its own production processes as clean and eco-efficient as possible. It concerns also optimising the added value (economic, ecological and social) of the sector and taking advantage of the new business opportunities sustainable development offers. Figure 3 gives these levels.
On the chain level chemical industry working together with suppliers and clients (which are also industries as building, food production, car manufacturing etc.) should make that materials chain, from basic resource till 'waste' are as 'lean' and 'eco-efficient' as possible and that 'the material chain is closed' by minimising losses and reuse.
On the societal level chemistry phases the challenge to develop and supply the means: materials and products, which can supply in a sustainable manner in the needs people have: energy, transport, food, housing etc.

Sustainable chemistry is commonly associated with the first two levels only. The 'Planet' aspects (environment, resources, ecology) are emphasized thus. The third level is at least equally important. Here in particular the 'people' aspects (prosperity, well-being, quality of life etc.) play an important role. Not only the eco-efficiency of chemical industry on sector or chain level is important but also the relation between production and consumption and the right way (also in societal responsible sense) to respond to the societal needs, locally and globally. Not just making 'products in the right way' but also making the 'right products'.

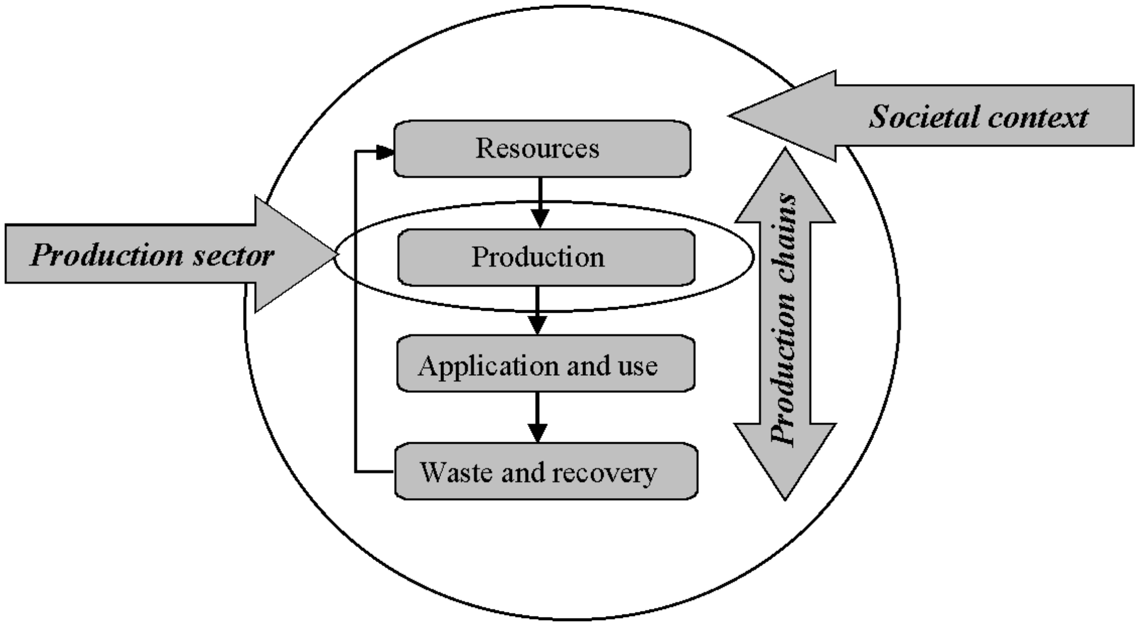

figure 3: Three levels of aggregation within chemistry

<u>Five pathways for transition in chemistry as defined in the study</u>
There is a variety of opinions regarding the overall direction of transitions towards sustainable chemistry. In our study we analysed the various views of opinion leaders and concluded that these could be clustered in five general pathways towards sustainability. Each of these five pathways constitutes of several developments, either of a technological or a societal nature, which is strongly interconnected and attribute to a coherent focus for chemical industries in the future. We distinguished pathways towards:

- optimised functionality of chemical molecules and products
- closed material chains and optimal processing of wastes
- biomass based chemical processes and products
- the clean processing of fossil resources
- ultra efficient process technologies

Of course these pathways do overlap and cannot be seen completely separated from one another. Nevertheless to determine the most important issues, they can be taken separately.

When discussing these pathways we should also be aware that chemistry as a production sector is very diverse. The sector comprises a large variation in 'ways of production', from large scale bulk production in the petro-chemical sector, to commodities, commodities, fine chemicals till the small scale production of high valued, functional products in the specialty chemicals sector. The dynamics, the markets, the relation with customers, the prevailing technologies etc. are different in these sectors. As will be shown, some pathways can be of major impact in one sector of the chemical industry, and largely irrelevant to other sectors. When policies are to be developed and projects are set up, this segmentation of the chemistry production sector should be taken into account. That offers different options as well as constraints for transitions. Other actions will be necessary to attain sustainable development in each segment.

Optimal functionality of chemical molecules and products

This transition pathway is of interest for three of the four sectors of chemical production: (pseudo)commodities, fine chemicals and specialty chemicals / pharmaceutical products. The main focus here is on developing a functionality of molecules and product, exactly fitting their use in products, materials and for instance in health care. At the same time their 'sustainable character' has to get good attention, such as toxicity, environmental effects on the long term but also the availability of resources needed and the efficiency of the production processes to produce just those components. Minimisation of wastes and of unwanted side effects will be attained when only those substances are made which are necessary for the 'job' they are designed for. Other developments are the development of lightweight and stronger materials which can lead to energy savings when they are used (for instance in cars).

Present developments in the field have made improved functionality of compounds possible in many fields already such as in the pharmaceutical sector (less side effects of medicines) and in the fine chemicals sector (purer reagents).

Furthermore other aspects of sustainability of materials and end products should be taken into account. Here better functionality means better adapted to societal demands. A case is the development of polymers that are better suited for recycling, for instance in products with a relatively short economic cycle (i.e. mobile phones). In all these cases it is not just the design of new molecules one should focus on but also the way in which they will have to be produced. New equipment and totally new processes are needed to produce those new compounds and to use them, in a sustainable way.

Quoted from opinion leaders

The **demand for new molecules is already growing rapidly** for better functionality of products, stronger and lighter materials. Drivers for this are the pharmaceutics industry, conservation of food, nanotechnology, microsystem technology, transport and space technology.

Chemistry plays **an essential role in sustainable energy** developments. Examples are the development of photovoltaic cells for harnessing solar energy. Two routes are possible, super efficient based on semi-conducting metals of cheap organic ones. Also a hydrogen based energy economy will ask much from chemistry: efficient production of hydrogen (eg biomass based, membranes, storage systems (strong and lightweight materials) etc.

Fine chemicals but also pseudo-commodities represent an enormous number of different compounds due the large variety of applications. When we are able to design molecules even better for an optimal performance in the intended application, their number will grow immensely. All those have to be produced. Production will often be in **relatively small volumes and will require rapid process changes**. What we need are therefore processes and installations that can switch simply and between processes, which are efficient in the use of energy and resources and have no emissions. Miniaturised and 'on demand' production are the key issues. This flexibility can also prevent that specific substances, due to 'economy of scale', dominate the market although they do not fulfil the specifications for a particular application optimally (technology 'lock-in').

Closed material chains and optimal processing of wastes

This transition pathway is of interest for a large part of the chemical production sector, from the bulk and petrochemicals, (pseudo)commodities and fine chemicals.

The focus of this pathway is on closing the material chains and on minimizing the input and output of materials and energy in the chain. Substantial reuse of materials should become a principal part of the structure of parts of the chemicals sector. To attain that in all steps of the production chain new choices must be made and processes and equipment have to be adapted, not only in the last (or first!) step: the processing of the waste. To optimise such reuse in whatever form, methods and procedures for selection of materials, design of products, reuse methods etc. must be adapted to create for optimal reuse possibilities. When new chemicals, polymers, basic materials etc. are being developed, a requirement will be that reuse and recycle can be done efficient and with minimal loss. Besides, processing and treatment of wastes and remaining materials has to be developed further for cleaner and more efficient waste management.

Quoted from opinion leaders
Short cyclic consumer products (certainly packaging) should not be based anymore on fossil resources. There are plenty of opportunities to use simple renewable resources for that. Society will in due course demand reengineering of these products and their use on the basis of the concept of the planet as a confined system.
Products and materials **should be kept inside the material recycle chain**. They will have to be designed for that. In the future a methodology will be available to calculate what form of recycle is the optimal one for specific materials; reuse of the product, the basic material or as the original basic components.
Closed production chains will have to be managed. Knowledge on what is done in every step of the production chain, will be essential. Cooperation in the production chain is necessary because the subsequent producers become more dependent on each other. Problems (such as wrong specifications or pollution) can lead to 'reputation damage' and high costs due to claims (compare for instance with the situation in the food industry).

Biomass based chemical processes and products.
The third transition pathway focuses on a major shift from the predominant fossil fuel based production processes towards biomass based processes. This pathway is of relevance for the fine chemicals sector on the middle long term and possibly for the (pseudo)commodities sector too on the long-term and even for some parts of the bulk chemical sector. For the specialty and pharmaceuticals biomass based routes, through biotechnology, are quite common already. It means the extensive use of renewable resource to produce basic components for further processes and materials, for example in construction, car parts etc.
Important here is the fact that chemistry, energy and agriculture must become to some extent interdependent, in new ways. That replaces the present interdependence of energy and chemistry which are now both largely based on oil. And because agriculture has also the very important function as supplier of food, such new function, must be assessed carefully. Multiple use of crops is an important option therefore.
Crops will be raised and harvested for use as raw materials for the production of chemical compounds or bio-fuels. This contributes to the closing of the atmospheric carbon cycle. Basic compounds which can be produced from crops are, among others, ethanol, ethylene, propylene and butylene. But also sugars, for instance derived from cellulose containing wastes can be used directly in processes based on bioconversion. Furthermore specific substances that are isolated from certain plants can be used (and already are) for the production of a variety of different often complex molecules and compounds. Through cultivation and selection and through genetic adaptation the yield of such substances can be increased and also other substances can be made. An example is a modified potato that instead of mainly amylose only amylopectine produces. That is a basic substance for a range of food and non-food applications.

Quoted from opinion leaders
In 2050 **a substantial part of the resources for chemical production will supplied by biomass**. On global scale there is sufficient biomass without threatening the food supply, even for a growing population. It asks for a different way of looking at and working with biomass, in agriculture as well as in chemistry. Multiple use of plants and crops will be normal and the production chains for these resources will be made more optimal and use quite different processes pathways then the present that are based on classic (fossil) resources. That requires a novel combination, and a sort of 'fusion' of biotechnology and the more traditional chemistry and engineering.
The use of biomass shall to a large extent occur **by local and relatively small size conversion** of material from different sources. The thus concentrated material will be transported to users directly or to central processing units. A local infrastructure will exist that will be on this level simple and will require only small investment. Large scale processing of raw biomass can take place where due to large scale agricultural activities biomass residues come available on large scale too.

Clean processing of fossil resources

A fourth transition pathway concerns the development of much 'cleaner' process pathways but still based on fossil resources such as oil and natural gas. These are developments which mainly will be important for bulk and petrochemical production sector. It is expected that much can be gained here, without turning away from such non renewable resources. In the opinion of most persons involved in the discussion that would also be impossible for the coming 50 years or so. Actually the ecological footprint of for instance the production of ethylene and propylene is already continuously become smaller the last decennia thanks to increased efficiency and up-scaling of production. Economic motives (lower costs) and ecological and environmental motives (less wastes and emissions, also due to more stringent regulation) join forces. By the use of efficient process technology, novel catalyst and intelligent process control systems (fossil) resources are being converted into useful products more efficient and less waste. By-products are more often used profitably. Compared to the use of fossil resources for energy production and for transport the use for (petro-)chemical production can be seen as very efficient and much more valuable. In view of that and accounting for the only small percentage of these resources that is used for chemistry, they propose to restrict the use of such valuable resources to chemical products only. Combined with a better closed material chain through effective recycling, there would be no shortage for this function in any timeframe.

Quoted from opinion leaders

Due to the high added value in the production chain it is likely that the the bulk petro-chemicals production sector is able to acquire sufficient resource material, even when oil and natural gas would really become more scarce. **Those will stay the dominant resource for chemistry**. Only in specific market niches biomass will be able to substitute oil s preferred resource.

Globalisation of the economy will lead to the transfer of labour intensive (and relatively much waste producing) fine chemicals production to low wage countries. The bulk chemicals production however -in which automation is very extensive - is likely to stay in Europe.

Fundamental changes, e.g. 'disrupting innovations', are less likely to occur in the bulk and petro-chemical sector also due to its large scale character. The main movement will be **continuous improvement** of energy use efficiency, and the environmental and safety performance.

Clean and ultra efficient process technologies

Finally, the fifth transition pathway that has been defined, impacts the whole chemical industry, from bulk till specialty chemicals. The key element of this pathway is a rigorous downscaling of conversion processes, implying much smaller equipment and installations, and implying extremely high conversion efficiency. This will result in a much more energy and material-efficient production process, and in a sensational reduction of wastes and emissions. At present, the (batch) production processes for fine chemicals, for instance, produce relatively much waste and are rather inefficient, largely due to the many steps that some synthesis pathways require. Many of these processes have become more efficient and cleaner in the last decennia; they are however not fundamentally changed. In chemistry and engineering new processes, equipment, processes are being developed for such fundamental change in the character of chemical production. Many disciplines work together: organic synthesis, (bio)catalysis, (bio)process technology, microsystem technology, separation technology. The aim is more 'elegant' processes which have much higher 'precision' and functionality, are faster, use no or less solvents, and are more efficient in the use of energy and resources. An important line of development for this is decreasing the number of synthesis steps. Another line is the development of miniaturised processes (with equipment on micro-level: 'chemistry on a chip') for which upscaling can be done 'easily' by placing many of such systems in parallel. Such developments are based on the use of microsystem technology developed for instance in the pharmaceutical industry where it is used to screen many components for their activity fast and many at the same time. What is seen here is a movement seen in many other areas of chemistry and engineering development: new developments in specialized areas and often small production sectors are taken over in other areas and larger production sectors. At the same time some developments in the smaller sectors are clearly inspired and stimulated by knowledge from the larger production sectors, for instance continuous reaction systems, common in bulk and pseudo-commodities, are being introduced in the fine and specialty chemicals sector too.

Also multifunctionality of (small size) production systems is thought of, by making use of ‘smart catalyst systems’ that can be adapted easily. It is envisaged that such changes can actually decrease the effect of ‘economy of scale’ and thus make for instance ‘in situ production’ of the compounds needed by a customer possible. It is safer, requires less transport and is the optimum solution for ‘just in time delivery’.

Visions by opinion leaders

‘Zero pollution production’ becomes feasible. Also in the fine chemicals sector molecule efficiency will near the ‘optimum’ through the use of completely new production processes such as using novel combined catalyst systems.

Green process technology will imply also **different and novel process control systems and concepts.** That will make quite different types and set-ups of production plants possible. Economy of scale will not be the most important driver, small scale production could be more optimal in different cases. It will change the logistic aspects too. Large scale production on a centralised site is not self-evidently the most economical option.

In the future even bulk chemicals production will take place in relatively small production halls instead of in the hugh installations we are so proud of sometimes. That is due to a combination of much faster processes giving much higher one-step conversion (thus less recycle) and higher selectivity (thus less removal of side products). The actual reactors are presently only a small part of a total installation and even those can be reduced in size with still the same throughput.

A shift is possible to production methods where **production of all intermediates can be done on one site**. So transport of sometimes hazardous compounds becomes unnecessary. Also storage of such compounds can be kept small because in situ use is feasible. When transport is still necessary intermediate compounds will have to be selected that pose much lower risks. High transport risks will not be acceptable.

4. DRIVERS AND BARRIERS FOR SUSTAINABLE INNOVATION

The developments described in these areas can certainly promote sustainable development in chemical industry and the economy as a whole. But that will only happen if that new knowledge is used and new technologies are implemented.. As yet that appears to be hardly the case, as is also confirmed by most ‘opinion leaders’ we interviewed. Of course fundamental changes can be expected to be time consuming. But that is only part of the reason why the implementation of these new technological options described previously, is lagging behind.

<u>Technology development is ‘only’ an ‘enabler’</u>

A notable aspect of many initiatives taken to promote sustainable development in chemistry is the strong emphasis on technology development. It is also an obvious reflex of scientists, engineers and managers alike, to concentrate on new knowledge in particular technological when discussing and promoting innovation. And of course new (chemical) technology is important and can even be a key factor. Technology is as such a so-called ‘enabler’: it is an essential part of such changes. However developing enablers is in itself insufficient to bring about changes and innovation, and certainly not ‘transitions into an sustainable economy’ which ask for changes in complex systems comprising of many non technical components too, as discussed before.

So the development of new chemistry and chemical technology does not lead automatically to the implementation and actual use of that new knowledge. We need to focus much more on the factors and conditions that determine I whether and how new technology actually is applied. And at the same time chemistry must put itself the question if the new developments that are investigated not only can contribute potentially to sustainable development but also in actual practice, in the long term, meaning it can lead to ‘system innovations’ that are feasible not only technological but also social, cultural and economical.

<u>Drivers and barriers influence the direction and speed of innovation</u>

Much more knowledge is needed to understand the stimulating and the retarding factors: so-called drivers and barriers of innovation and progress towards sustainable development. As said in the introduction this was the main objective of this study and formed the main part of the discussions with the ‘opinion leaders’ representing all relevant stakeholders. Specific questions raised were intended to make an inventory the major issues and their potential positive of negative effect. Those issues are very varied and include:

- societal and economic trends, at the national and the international/global level;
- legal measures, international policies, financial incentives such as subsidies;
- the corporate culture: the dogmas and paradigms existing within industry;
- economic structures and national and international markets and trade relations;
- mechanisms that determine introduction on the market and viability of niche markets.

Example of drivers
The Kyoto protocol aimed at reducing CO2 emissions will clearly be a driver. The possibility of trading such rights, between countries and between businesses, will stimulate the implementation of technologies that reduce the use of energy and those that make it possible to remove CO2 from flue gas and store it. Already it leads to more combined power and heat production and changes to processes in which both can be used more in balance. Small scale applications, such as in offices and houses, become feasible.
Concerns about the stability of oil supply and the rising prices are a clear driver. The latter is due to political instability in the oil producing countries but is also caused by increasing demand in growing economies such as China and India and the gradual exhaustion of the 'easy to exploit wells' we were used to the last century.
Views and industrial ambitions can make good drivers too: such as the view that in the (near) future hydrogen will be used for fuel and for heating purposes in buildings.
And of course public indignation about pollution, risks etc. are clear drivers, the responsible care program is based on it. Communication will not suffice, innovation is the only solution.

Examples of barriers
Technology lock-in is an often observed barrier. Expectations and way of use by clients, design of products, equipment in which it is used etc. are totally focussed on established technology. A fundamentally new technology, even when it is better, has many problems getting accepted, if at all. It is well known in electronics, the first on the market sets the standard. An evident example in chemistry is forme by the oil based processes and products. Other resources such as biomass are seen as inferior because the known products cannot easily be made from them. But they could supply better products, industry is not accustomed to. A specific case is detergents based on petro-chemistry oil and those on modified vegetable oils.
Reuse of polymers is severely hampered by the fact that there are as yet no accepted tests and quality guarantee procedures. When producers propose to use recycled polymers for a product to customers a procedure is actually developed on the spot. That is if a customer finds recycled polymer acceptable at all. Producers claim that in many cases recycled polymer is as good as virgin material. There appears to exist a resentment against reused and recycled materials that is not based on rational grounds. In some branches that is not a problem at all, on the contrary, such as for cars, bottles, copiers, machinery. But for materials as such, that is still a problem.

<u>Uncertainties and dilemmas may prevent joint actions</u>
At the same time it is clear that implementation of new technologies and approaches, use of knowledge and the drivers for change in a certain direction are hampered also by the lack of knowledge in certain fields, uncertainty if the effects wished for are indeed attained and no 'rebound effects' occur. Besides in many fields dilemmas occur because compromises are needed and risks must be taken. That is often worsened by the confusion and the misunderstanding that exist around the concept of sustainable development. The most common one is that sustainable development is just extra measures for a better environmental performance bringing higher costs with it. But it concerns the viability of a stable society and the economy that is needed for that in the long run, and therefore of industry itself too. Such uncertainties and dilemmas can be bypassed sometimes to a certain extent. But most are inherent with the complexity that is part of sustainable development and the wide range of opinions and values that exist within a society, within the chemical sector and even within a company.

Examples of dilemmas and uncertainties
Biomass as source of chemicals instead of using it for food is still an ongoing discussion. Many facts are given. However they are often very contradictory and besides even the same facts are interpreted in very different way. Opinions and feelings determine the discussion to a large extent. It seems that there is ample biomass as well for food as for chemistry and even some for energy, certainly when the waste part of a crop after harvesting and processing is used. That can amount to 90% of the total plant material. Nevertheless that discussion interferes with decision making and slows also technology development.
New investments seem/are always more expensive than continuing to use the existing installations even when much maintenance and upgrading is needed. In the long run the new installation might become cheaper but only if it can be used during a sufficient long period. That is always an uncertainty of course. Besides: you know the peculiarities of the existing plant and those of a totally new plant are unknown. Even if it is cheaper the financial risks are higher then continuing with the old one.
Coping with unknown risks when introducing new compounds is a clear dilemma. Of course many tests are being done, as is required. REACH will add to that. However there it was clearly stated during the discussions that industry had already too many surprises and environmental groups still find much of that insufficient. Some effects will only become apparent in the long run. We look for the problems we know. Do we know all?

<u>‘Issue-arenas’ for transitions</u>
Those barriers, drivers and dilemmas must be known and understood much better and with it the conditions and factors influencing them. The present lack of insight in these forms an enormous obstacle for transitions towards a more sustainable chemistry. Information concerning those will have to be gathered from many sources. Many studies are available on specific transition pathways and on particular barriers and dilemmas. However a more complete inventory of all those is needed for specific transitions in transition areas that have been defined as being essential for a future sustainable economy, for government, industry and the other actors involved.

To bring all the relevant issues together that form those enablers, drivers, barriers and dilemmas/uncertainties the authors have developed an approach to map these: a so-called 'issue arena'. It forms the matrix that facilitates an overview of all relevant issues. To that aim issues are not only divided regarding their role and influence on innovation and transition, but also regarding the level on which their influence is the largest and on which actions must be taken concerning them. The example of the issue arena on biomass based processes and products, presented in figure 4, was based on the interviews and the discussions with opinion leaders, supplemented with earlier studies, in particular to make a good overview of the ‘the various technology developments which offer opportunities for fundamental innovations.
It gives a broad range of issues, all supported by most of the respondents. Many of the issues raised, are relevant for the other transition areas as well.

Figure 4: Issue-arena for 'biomass based processes and products'

Enablers	**Driver**	**Barriers**	**Uncertainties /dilemmas**
Level I: societal context			
# Societal and political basis for climate policy (Kyoto protocol) # 'Biological origin' gives 'sense of quality' # Needed income for farmers and better means for existence in rural areas # Chemistry sector has a high awareness of its responsibilities (and bad name due to past incidents) # Quality of life is growing issue	# Levies on CO_2 and fossil resources # Growing costs for hazardous wastes # Active policies to promote small scale industrial activities in rural areas # International (EU) and national directives on waste reduction, cleaner production and safe chemicals	# Low priced fossil resources # Societal resistance against genetic modification# Strong competition between research groups and between national interests: dispersion of efforts [a]) # Insufficient innovation awareness [a]) # Inconsistency of policies and regulations	# Competition with food production # Large land areas needed in competition with other uses due to growing population and space for 'biodiversity' # Effects on imbalance between industrialised and non industrialised countries eg by low prices for raw biomass (as it is the case for food)
Level II: chain context			
# In Europe more land area comes available due to overproduction # The options for biomass based energy increase with multiple use of biomass # Waste treatment by combustion is a non polluting option for biomass	# more options for energy based on biomass waste streams	# Renewable resource use asks for a new production structure throughout the chain # Getting acquainted with new substances and new possibilities # different organisation and in culture in chemistry and agricultural sector # Innovations in one link are not accepted easily in other links of the chain.	# Real 'profits' for environment and sustainability hard to determine # Distribution of costs and profits over the various steps in the production chain # Uncertainties about the best routes to use biomass # Much coordination might be necessary in such production chains
Level III: sector context			
# Much new knowledge and novel technology available # Constant demand for new compounds with often higher complexity # Active platforms for inter- and transdisciplinary cooperation (energy / chemistry / health / food / agriculture) [a)]	# Demand for clean and safe in situ production options, on small scale # higher costs for environmental measures # Total plant conversion (such as 'Cascade approach and Bio-refinery approach)	# Technology lock-in # Complexity of basic materials # Large variety in production routes. # Seasonal availability of biomass # Storage, biomass is quite perishable # New technologies have to compete with old but still running processes/installations	# Import options of biomass # long term prospects of availability of specific biomass wastes # No good model for determining integral costs and profits # Precautionary principle
[a)] these issues concern of course the Dutch' situation but are to some extent relevant on a broader level too			

5. CONCLUSION

Technological development acts as an enabler in the transition towards sustainability in chemistry, engineering and industry. In this paper we have described five pathways for transition in chemistry, based on interviews with some 45 Dutch' opinion leaders, in each of which new technologies are vital to change. Each of these five pathways constitutes of several developments that are strongly interconnected and attribute to a coherent focus for (specific sectors within) the chemical industry in the future. We distinguished pathways towards:

- optimised functionality of chemical molecules and products
- closed material chains and optimal processing of wastes
- biomass based chemical processes and products
- the clean processing of fossil resources
- ultra efficient process technologies

Together these pathways express a wide diversity, both in terms of various sectors within the chemical industry, as well as in terms of contrasting visions regarding the direction of sustainable innovation in chemistry and engineering.

Technological development is a vital key to each these transition pathways, but in itself not sufficient to bring these transition about. Through discussions with the Dutch' opinion leaders we learned that the actual implementation of the new knowledge and new technologies is lagging behind. A phenomenon called the 'innovation paradox' in recent Dutch' policy debates. The opinion leaders' pointed out various drivers, barriers, dilemmas and uncertainties in the innovation processes, as being at least in part responsible for this paradox to occur in chemistry and engineering. Not unexpectedly, it became clear that the major impediments are of an economic, institutional and cultural nature. Of course, this is only a first study on the (Dutch) situation concerning sustainable chemistry transitions and the apparent innovation paradox observed here, should be elaborated much more deeply.

In this paper we captured the relevant enablers, drivers, barriers, dilemmas and uncertainties in a so-called issue arena. The issue-arena is a means to structure the dialogue between policymakers, industry, scientists and societal organisations; a dialogue concerning the factors and conditions that hamper or might promote the actual implementation of new and promising technologies. In addition to a shared vision regarding the transition pathway, a common understanding of these factors and conditions is needed. By involving in this dialogue many stakeholders from various backgrounds, it is possible to create the essential basis for joint actions of industries, government, research organisations and other societal stakeholders. Each actor can act within its own sphere of influence, thereby contributing to an overall strategy towards sustainability. And although we believe that government must take the initiative to such a concerted action, government action alone surely is not enough. Actually it is the chemical industry that has the keys to open up this 'innovation paradox'. R&D-initiatives, in which industry and science cooperate, driven by the economic perspective of new sustainable business, will provide the momentum needed to bring about sustainable development in chemistry, engineering and industries.

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